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DESIGN OF COST-EFFECTIVE RELIABLE SOLAR HEATING SYSTEMS

A design guide based on the proceedings of the October 7, 1986 E M R Workshop

RENEWABLE ENERGY BRANCH

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PREFACE

This report is a summary of a workshop held on October 7, 1986 in Ottawa. The workshop was a round-table discussion by 35 of the top Canadian solar designers on techniques for designing cost-effective, reliable solar heating systems. The workshop (and therefore this report) specifically excluded the design of solar collectors, air-based systems and residential solar systems.

This report is meant to be a design guide for engineers, designers and installers of liquid-based commercial/industrial solar heating systems. It has been assumed, however, that the reader understands solar heating concepts and system design. It is suggested that those readers unfamiliar with basic solar system design read some of the many introductory texts on the subject. Although this report is based on the discussion at the workshop, additional information is included where necessary in order to provide a more complete understanding of the topic.

The information given in this report is meant to be state-of-the-art at the time of publication. It should be remembered, however, that solar components and system design procedures are constantly being improved. In addition, a one-day workshop cannot cover all aspects of solar system design and, as such, this report is not meant to be a complete design guide. The information contained in this report should be supplemented by other design guides, good engineering principles and common sense. Many of the techniques given in this report are only suitable for certain solar applications, designs and climates. The reader should understand the principle of the technique and apply the technique only where it is appropriate.

ABSTRACT

The objective of the report is to present technologies that active solar designers have used to reduce system costs and improve system performance and reliability. The report is based on the discussions from a one-day workshop attended by 36 Canadian solar designers. The discussion covered nine main areas: solar application evaluation, site evaluation, system design, rack design, storage design, heat exchanger selection, control requirements, piping design and pump/valve selection. The report presents over 50 techniques that can be used to improve the cost effectiveness of liquid-based active solar heating systems.

EXECUTIVE SUMMARY

This report is a summary of an active solar design workshop held in Ottawa on October 7, 1986. Thirty-six designers discussed techniques for reducing system costs and improving system performance and reliability. The discussion was restricted to liquid-based commercial/industrial solar heating systems.

Designers noted that by prudent selection of application and by proper sizing, solar heating system performance could be dramatically improved. System costs can be reduced by eliminating the need for a system component (e.g. storage tank, heat exchanger) through efficient design.

Accurate estimation of the water heating load was seen as a major problem for proper system design. Hot water consumption metering and analysis of fuel and water bills were given as techniques to estimate hot water consumption.

For most solar applications designers chose drainback systems. In some cases (e.g. slight difference between collector and storage tank heigths) antifreeze systems would be the preferred system

In general, ground or wall mounting of collectors is cheaper than roof mounting and wood racks are cheaper than metal racks.

Storage tank costs can be reduced by using plastic instead of metal tanks. Tank performance can be improved by promoting thermal stratification.

System control was seen as an area for improvement. All systems should incorporate collector fluid boiling and freezing protection independent of the main controller. Additional diagnostic and monitoring equipment would be of benefit for most systems.

Piping and pipe insulation costs can be reduced by minimizing exterior piping.

SOMMAIRE

Le présent rapport est le compte rendu d'un atelier sur la conception des systèmes solaires actifs qui s'est tenu à Ottawa, le 7 octobre 1986. Trente-six concepteurs ont discuté de techniques visant à réduire les coûts des systèmes et à en améliorer le rendement ainsi que la fiabilité. Les discussions se limitaient aux systèmes de chauffage solaire commerciaux et industriels équipés de capteurs et utilisant des liquides caloporteurs.

Les concepteurs ont remarqué qu'il était possible d'améliorer considérablement le rendement des systèmes de chauffage solaire en considérant soigneusement leur application et en déterminant leur taille optimale. Le coût des systèmes peut être réduit en éliminant le besoin d'une composante du système (par ex. un réservoir de stockage, ou un échangeur de chaleur) grâce à une conception efficace.

L'estimation précise de la charge de chauffage de l'eau représente un problème important pour la conception des systèmes. On propose le métrage de la consommation d'eau chaude et l'analyse des factures d'énergie comme techniques d'estimation de la consommation d'eau chaude.

Pour la plupart des applications, les concepteurs ont choisi des systèmes à vidange. Dans certains cas (par ex. faible différence de hauteur entre le collecteur et le réservoir de stockage) on a préféré les systèmes à antigel.

En général, il revient moins cher d'installer les capteurs au sol ou sur les murs que sur le toit et les supports de bois sont plus économiques que les supports de métal.

On peut réduire le coût des réservoirs de stockage en utilisant des réservoirs de plastique plutôt que de métal. Le rendement des réservoirs peut être amélioré au moyen de la stratification thermique.

Il semble qu'il y ait place à l'amélioration pour ce qui est du contrôle des systèmes. Tous les systèmes devraient comprendre un dispositif de protection du fluide contre l'ébullition et contre le gel, indépendant du contrôleur principal. L'installation d'équipement additionnel de diagnostic et de contrôle serait avantageux dans la plupart des cas.

Les coûts de tuyautage et d'isolation des tuyaux peuvent être réduits en minimisant le tuyautage extérieur.

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1. INTRODUCTION

This report is a summary of a workshop held on October 7, 1986 in Ottawa. The workshop was a round-table discussion by 36 of the top Canadian solar designers on techniques for designing cost-effective, reliable solar heating systems. The workshop was structured to discuss the nine steps in solar heating system and component design:

1) solar application evaluation
2) site evaluation
3) system selection and design
4) collector support rack design
5) storage system design
6) heat exchanger design
7) system control and operation design
8) piping design
9) pumps, valves and miscellaneous equipment design

This report discusses the main factors that the workshop participants considered important in reducing system costs, improving performance and providing long-term reliability in each of the nine steps.

The first three steps can be considered the preliminary design. The objective of the preliminary design is to assess the economic viability of the proposed solar application. By evaluating the application and site, the designer can determine the system size, required components, projected cost and estimated fuel savings. If the project is economically attractive to the customer, the designer can proceed with the detailed design (Steps 4 to 9).

The objective of the detailed design is to optimize system and component size and economics. After having selected the collector type, the designer must design the remaining six system components. Because of the complex interaction of system components it is usually necessary to use a computer program, such as WATSUN, to optimize component and system size.

2. SOLAR APPLICATION EVALUATION

The workshop participants discussed which solar applications provide the best economics and which building sectors have been the most receptive to solar heating. In addition, current solar system costs were presented.

2.1 Current Solar Applications

Over the past ten years there has been a rationalization of which heating applications should be met by solar energy. Currently most solar heating applications meet two criteria:

- heating is required for a large quantity of cold (mains) water
- building owner is interested in medium term payback times (i.e. approximately five years)

In order to achieve a reasonable payback period, solar heating systems are being used to heat water from mains a few degrees and use the conventional water heater to bring the water up to the required temperature. Under this condition solar heating systems can supply over 2.5 GJ of energy per unit of collector area and conceivably as high as 4 GJ/m^2 depending on the water load profile. The most common building types for solar installations are apartment buildings and nursing homes followed to a lesser extent by motels, restaurants, indoor swimming pools and fish hatcheries. Many industries require large volumes of heated water. They do not, however, meet the second criteria. Most industrial building owners are only interested in projects that pay back in less than two years. Thus while many industrial applications are well suited to solar heating, solar designers have found industry sales very difficult. Interestingly, many of the building sectors that are using solar heating can be characterized as having a fixed revenue base and can increase profits only by reducing costs (e.g. apartments and nursing homes).

Many solar designers are focussing on one building sector. The similarities between buildings helps reduce the design costs and a single, more definable marketing plan can be set up.

2.2 Current Solar System Costs

Solar Commercial/Industrial projects recently funded by Energy, Mines and Resources Canada have an average installed cost of $\$420/m^2$ with some projects costing as little as $\$300/m^2$. Approximate component cost breakdowns are given below in order of decreasing cost.

Component	Typical Cost ($/m²)
Solar Collectors	150 - 175
Collector Support Rack	40 - 50
Design and Execution	40 - 50
Profit/Overhead	30 - 50
Labour	35 - 50
Piping	20 - 30
Storage Tank	20 - 30
Insulation	15 - 20
Heat Exchanger	10 - 20
Pumps and Valves	10 - 20
Electrical/Controls	10 - 15
Building Modifications	5 - 10
Approximate Total (All Components)	$450

It should be noted that for any particular project some of the above components will not be necessary (e.g. storage tank, building modifications). In fact the most cost-effective systems are those for which several of these components are not required.

Other than the solar collectors, there is no single large cost component. In order to reduce system costs, the cost of all components must be reduced. Collector support rack and design costs, as the second and third largest costs, seem to be the best starting point to reduce costs.

3. SITE EVALUATION

If the proposed solar heating application is a good one, the first step in the design process is to do a site evaluation. The workshop participants discussed the two factors affecting site evaluation: building physical constraints and size of water heating load. Accurate determination of the water heating load was considered by the participants to be the most critical factor in system design.

3.1 Building Requirements

In general, there are few building physical constraints that would prevent the installation of a solar heating system. There are, however, many building features that affect the installation cost. If many of these features adversely affect the cost, a solar heating system would be economically unsound. Designers generally examine the following building features:

- roof construction and load bearing capacity
- orientation of building
- available roof or ground area for collectors
- location and available space in mechanical rooms
- conventional heating system and the fuel to be displaced

Most roofs are designed to such tight tolerances that collector location must be chosen carefully. The easiest (and cheapest) roof mounting technique is to attach the collector supports to the roof above the building support walls. Most designers would rather accept the slight performance penalty for off-south orientation rather than the increased costs for a more elaborate collector support structure. Likewise, if the roof is pitched, most designers would mount the collectors flush to roof and not attempt to make any correction to the collector slope. For some buildings, roof area is the determining factor in the size of the system. For buildings with high water heating loads and small roof area (e.g. laundromats, apartments), it may be necessary to find additional roof area or examine the possibility of ground or wall mounting the collectors.

Most solar heating systems will require some thermal storage. Generally the solar storage tank is located close to the conventional water heater in the mechanical room. The site evaluation should examine the horizontal and vertical distances (i.e. the piping run) between the proposed collector location and the mechanical room. The mechanical room (or a room nearby) should have sufficient space to accommodate the storage tank.

In assessing the cost effectiveness of a solar heating system, the cost of the fuel being displaced is extremely important. Although fuel prices vary across the country, in general system economics look best when displacing oil or electricity.

3.2 Water Heating Load Estimation

The size of the water heating load is crucial to sizing and designing solar heating systems. Oversizing solar heating systems reduces the solar energy delivered per square metre of collector and, thus, the system cost effectiveness. Oversizing may also cause the antifreeze in closed-loop systems to boil off. Many systems have been oversized because designers based their sizing calculations on design handbook values of "typical" water loads. Monitoring results indicate that for many systems actual water loads are only 40 to 60% of ASHRAE handbook values. Estimating the water heating load based on the size of the existing water heater has also proved to be inappropriate. Three techniques that have proven to be successful in estimating water heating loads are (in order of preference):

- direct measurement via a water meter installed in the hot water line
- calculation of hot water load from summer fuel bills
- calculation of hot water load from total water load

The designer would be well advised to make use of all three techniques for better verification and to identify seasonal trends.

Installation of a water meter in the water line feeding the conventional hot water tank is the most accurate method of water load determination. This technique is also the most costly and the most time-consuming. The cost of the meter can be spread over several projects

if the meter is installed for only a few weeks at each site. Alternatively the meter could be left in place and used as part of the monitoring system (as part of an integrating heat meter and for flow balancing). Svensk and Valmet equipment have been used successfully in this regard. The designer should be wary of seasonal variations in water demand. Use of the other two techniques would help indicate whether the period of water load monitoring was representative of annual hot water usage.

The second technique for water load estimation is to use monthly fuel bills and back-out hot water demand. This technique works best for natural gas water heaters during months when natural gas is used only for water heating (i.e. summer). The average daily water load (L) would be calculated as:

$$L = (C \cdot FC \cdot \eta_{heater})/((T_{hot} - T_{cold}) \cdot N) \quad \text{(in litres/day)}$$

where C is a conversion factor 8880 for natural gas, 9200 for #2 oil

FC is the monthly consumption in cubic metres for natural gas, litres for oil

η_{heater} is the seasonal efficiency of the water heater including effects of tank losses and recirculation loop losses, typically between 0.4 and 0.6

N is number of days in the billing period

T_{hot} is hot water setpoint in degrees C, typically 55-70°C

T_{cold} is the mains water temperature in degrees C, typically 10-15°C during the summer

As with the previous technique, the designer should check whether the period of fuel bill analysis is representative of annual water usage. Fortunately, however, the summer period is the most critical for solar design.

The third technique for water load estimation is to analyse monthly water bills. As an absolute upper limit the monthly <u>hot</u> water usage cannot exceed the billed monthly <u>total</u> water usage. For "people"

dominated water loads (e.g. apartments, nursing homes, gymnasia) the hot water usage is typically 25-35% of the total water load. The advantage of this technique is that seasonal variations in hot water demand can be estimated. The designer should be cautious, however, of seasonal variations in cold water usage such as lawn watering or vehicle washing.

4. OVERVIEW OF SYSTEM DESIGN

The two main factors in system design discussed at the workshop were system size selection and system type selection. The size and type of system generally determine which components will be needed in the system.

4.1 System Size Selection

As discussed in Section 1.1 most solar designers are sizing systems to heat mains water only a few degrees. Expressing this another way, most designers are sizing systems to achieve an annual solar contribution of between 20 and 40% of the total water heating load. Sizing systems to supply high solar contributions results in significantly reduced performance per square metre. In applications where the roof area is small or the water load large, solar contributions may be as low as 5 to 10%.

After the water load has been determined (see Section 3.2), the most important parameter in determining solar contribution is the collector area. At the preliminary design stage, most designers would simply estimate collector area (A_c) by

$$A_c = (Q_{load} \cdot F_s) / S$$

where Q_{load} is the total annual water heating load (in GJ) (see Section 3.2)

F_s is the desired solar fraction

S is the expected solar contribution per square metre, typically 2.5 GJ/m² for low solar fractions

Detailed sizing and optimization would be done later by computer simulation (e.g WATSUN computer program) when the client has decided to proceed, building factors have been taken into account and the other components have been selected.

4.2 System Type Selection

Based on the system size, building characteristics and load profile, the designer can select the system type. System types can be divided into four groups depending on the method of freeze-protection:

- seasonal or water-based
- antifreeze
- drainback
- draindown

Draindown

In draindown systems mains water is circulated directly through the collectors. When there is a danger of freezing, collector supply and return valves would be closed and the water in the collectors would be dumped to a drain. In the past, these systems have used solenoid valves to isolate the collectors. There have been several cases where the solenoid valves did not close completely and the collector water froze. As a result, most designers have avoided using draindown systems. Recently, however, spool valves have been used successfully in draindown systems. The stronger closing mechanism in spool valves means they don't have a tendency to "stick" open as is common with solenoid valves.

Seasonal

Seasonal or water-based systems have been used successfully for modest-size systems in the warmer parts of Canada. In the Vancouver-Victoria area "seasonal" systems have been operated year-round with no need for collector drainage. The main advantage of these systems is in the elimination of any heat exchanger. This reduces the cost, simplifies installation and improves performance (no heat exchanger penalty). For the rest of Canada, seasonal systems are best suited to summer only water loads such as small motels and camping shower facilities. If there is some winter load, an annual system would probably provide better system economics.

The critical design factor in seasonal systems is preventing freezing. All seasonal systems incorporate some method of freeze-protection (other than system drainage) and the trend is to provide double or redundant protection. This may consist of two freeze valves on every line or one freeze valve and heat tracing wire. Freeze valves appear to have operated reliably in preventing freezing, the main problem, however, appears to be in re-closing. Once a freeze valve has opened it may take fairly warm ambient temperatures before it re-closes. In the meantime a large amount of mains water will have leaked out. At the very least, the designer should provide proper drain facilities for this water.

Drainback

For all other systems, the designer must choose between using antifreeze or draining the collector fluid back to the storage tank as the method of freeze protection. The choice between these systems is one of personal preference, although designers are favouring drainback systems in most applications. The main disadvantages of drainback systems are the larger pumping requirement to overcome the collector-storage tank height difference and the concern for possible freezing if the water does not completely drain. If the designer has a concern about the complete drainage of collectors and associated piping, antifreeze can be used as the drainback fluid. The glycol will have a long life (over six years) in this application because it should never boil.

Large systems can be designed as drainback by simplifying the piping arrangement. Successful techniques used in large systems are connecting up to 40 collectors in each array and minimizing exterior piping by having separate piping roof penetrations for each array (see Section 9).

A commonly overlooked design factor in drainback systems is the length of time required for the water to drain out of the collectors. While the collector fluid is draining back through the pump, the pump should not restart as this would place an excessive load on the motor. If the water drainage rate is too slow, it is possible that some water could freeze in the collectors. Drainage can be slowed or prevented if

exterior air vents or vacuum breakers freeze. Most designers are avoiding the use of exterior vents since they cannot be relied upon during cold weather. Designers are also cautioned to remove the handle from any valve that, if closed, could prevent the collectors from draining.

Antifreeze Systems

Closed-loop antifreeze systems are generally used for large systems where collector drainage is difficult because of complex piping arrangements or lack of height between collectors and storage tank. The disadvantages of antifreeze systems are the requirement for an expansion tank and air purger, the need for an antifreeze refill system if the glycol boils out, and higher maintenance costs associated with changing the glycol every few years.

A key design requirement for antifreeze systems is allowing the system to refill if the antifreeze boils out. It is almost inevitable that at some time in the life of the system there will be no hot water demand for an extended period of time or the glycol circulating pump will fail. Under these circumstances the glycol might boil and be vented out the pressure relief valve. If glycol is not put back in when the glycol cools down the system may not be able to operate. The refill system should be automatic since the operator may not know the glycol has boiled-off or how to refill the system. To avoid steam explosions, the system should not be refilled while the collectors are at a high temperature.

5. COLLECTOR SUPPORT STRUCTURE

As discussed in Section 2.2, after the collectors, the collector support structure is often the most expensive part of the system. The workshop participants discussed the various locations for mounting collectors and cost-effective support structures. Because of the many techniques for supporting the collectors and the potential for cost reduction, the designer is well advised to examine this component in detail.

In designing collector support racks it is important to use a structural engineer experienced with solar heating systems. The National Building Code is open to interpretation in the design of collector support frames. A conservative structural engineer may over-design the racking system thereby increasing the cost of the system.

5.1 Support Structure Location

Collectors can be mounted in three locations: roof, wall or ground. In general, it is cheapest to construct a support structure on the ground. Ground mounting allows orienting the collectors due south, whereas this may not be feasible with roof or wall mounting. Ground mounting, however, may result in other costs, specifically longer piping runs and protective fencing. The usual limiting factors for ground mounting are the lack of available ground space and a concern about vandalism.

Wall mounting of collectors, although more expensive than ground mounting, is generally cheaper than roof mounting. In most wall-mounting cases racks are attached to the side of a building to slope the collectors. These racks must be anchored to the building support columns to withstand snow and wind loads. Although it may be cheaper to mount the collectors flush to the wall, vertical surfaces receive much less incident solar radiation than do sloped surfaces. The resulting loss in solar energy collected generally does not compensate for the installation cost savings. Difficulties with wall mounting include limited wall area and possible shading of collectors.

Most support racks are located on the roof. A key factor in system design is where to position the collectors on the roof. Designers try to locate the support rack where the roof is the strongest. Ideally rack support columns would be directly above building support walls. Lining up with the building support walls usually means that the collectors are not oriented due south. In so doing, the savings in support rack costs generally more than offsets the loss in thermal performance.

In some cases building support walls are spaced far apart (i.e. greater than seven metres) and the support rack must sit upon roof joists. It is better that the collector support rack run perpendicular to the roof joists and away from the centre of the joist spans (see Figure 5.1). In this manner all the loadings are spread over many joists. Many buildings have multiple roof levels or a penthouse. A good location for the support rack is to back against a higher roof level (see Figure 5.2). This technique eliminates backside wind loading.

In summary, the best choice of mounting location depends on the building. While the bulk of solar heating systems are mounted on the roof in some cases ground or wall mounting may be cheaper.

5.2 Support Structure Design

The type of support structure depends on the collector location. For ground mounted collectors, the support structure is usually made of pressure-treated wood. The wood is anchored to the ground using concrete posts. The solar heating system at Mohawk Laundry in Hamilton uses well-designed wood-frame ground mounted racks. Details of the rack are shown in Figure 5.3. An alternative to concrete posts is the use of a European system adapted by Petro-Sun to insert three metre long metal rods into the ground. A hook at the bottom end of the rod prevents the rod from being easily pulled out.

When designing a roof-mounted rack, two trade-offs must be examined: number of support columns versus size of frame support rails and number of support frames versus size of collector support rails (see

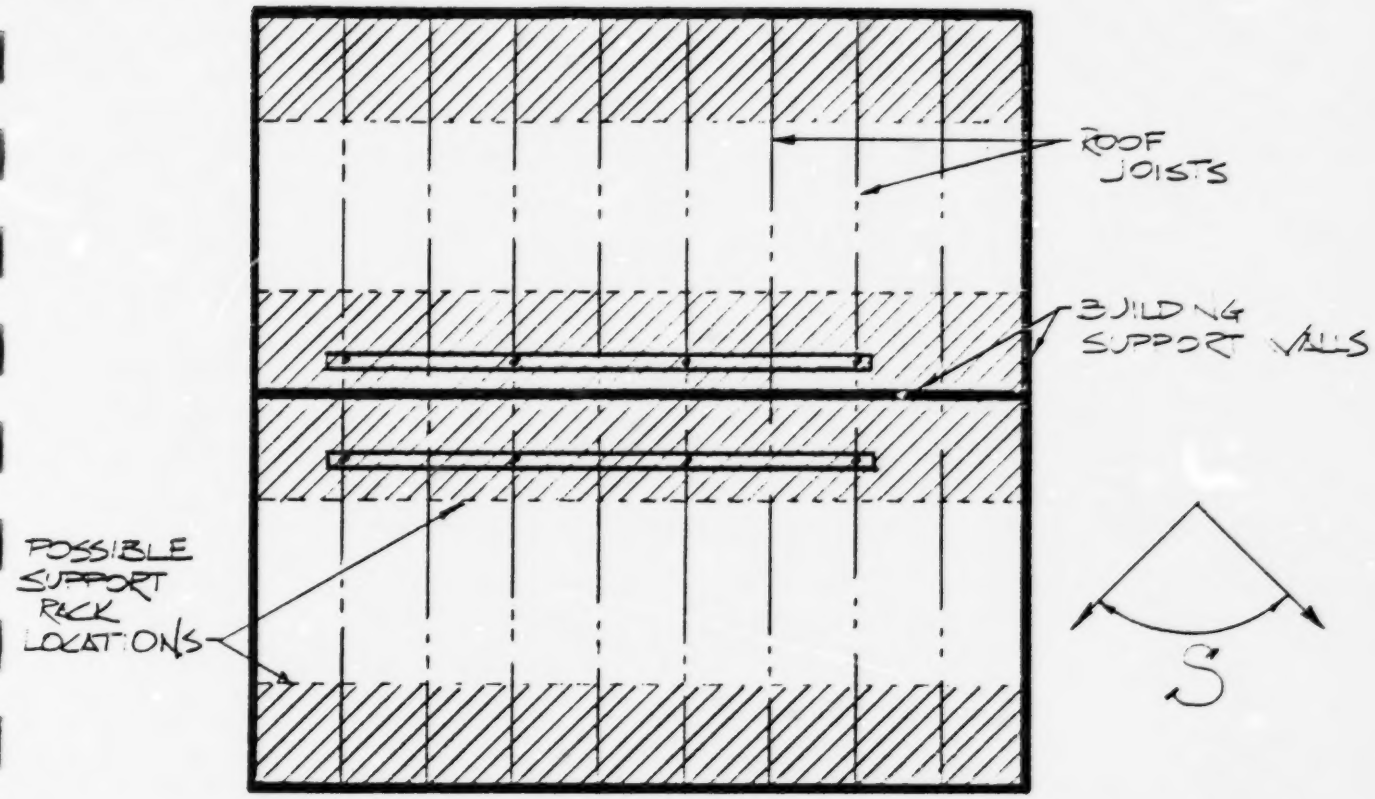


Figure 5.1 Recommended Collector Support Rack Locations

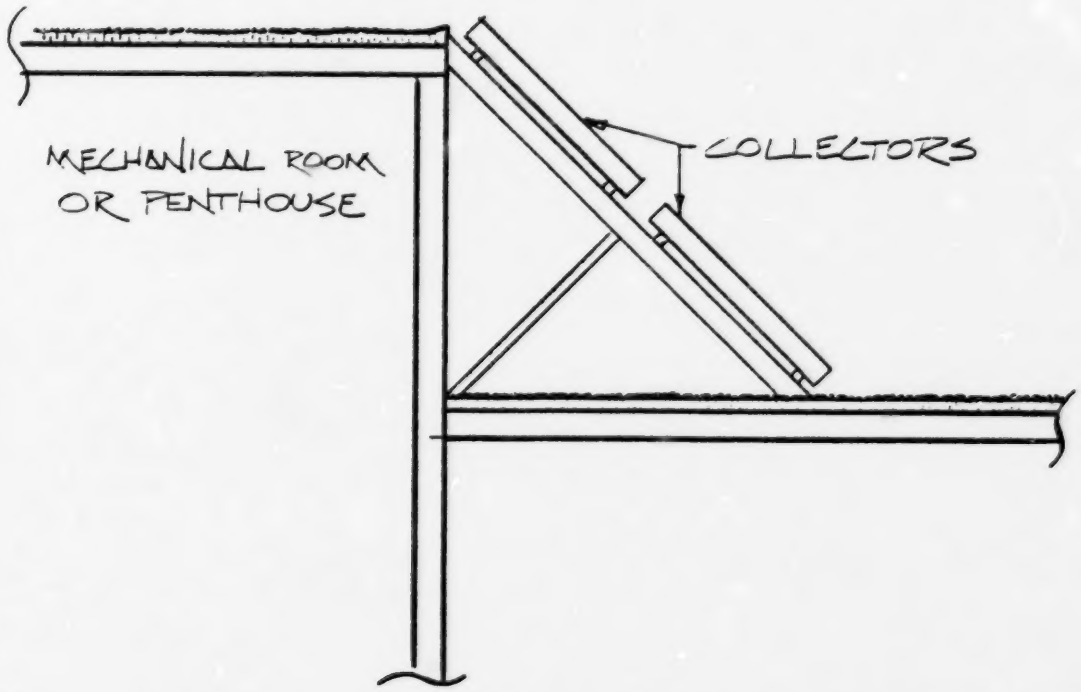


Figure 5.2 Possible Collector Location for Buildings with a Penthouse

Figure 5.3 Typical Wood Frame Collector Support Rack

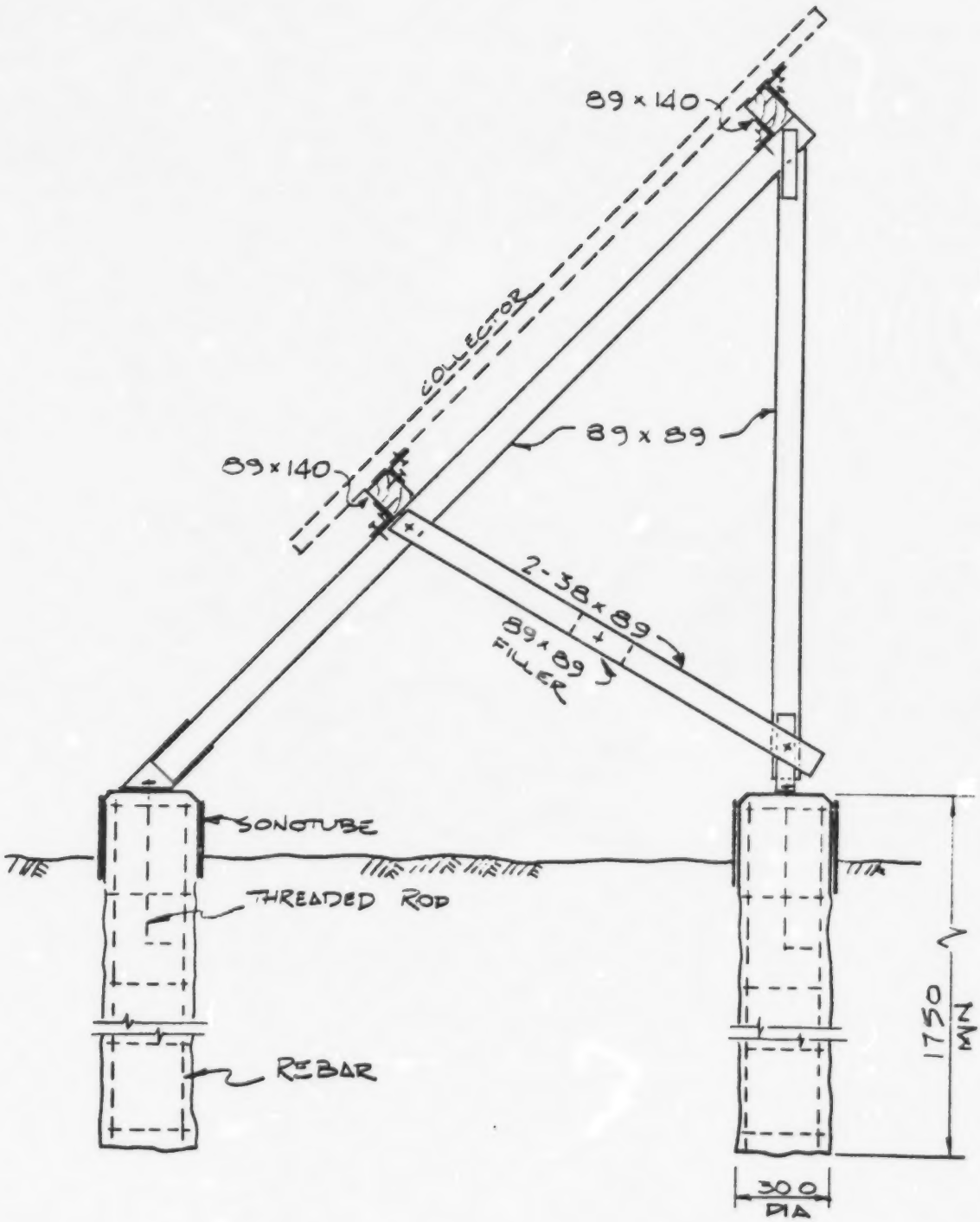
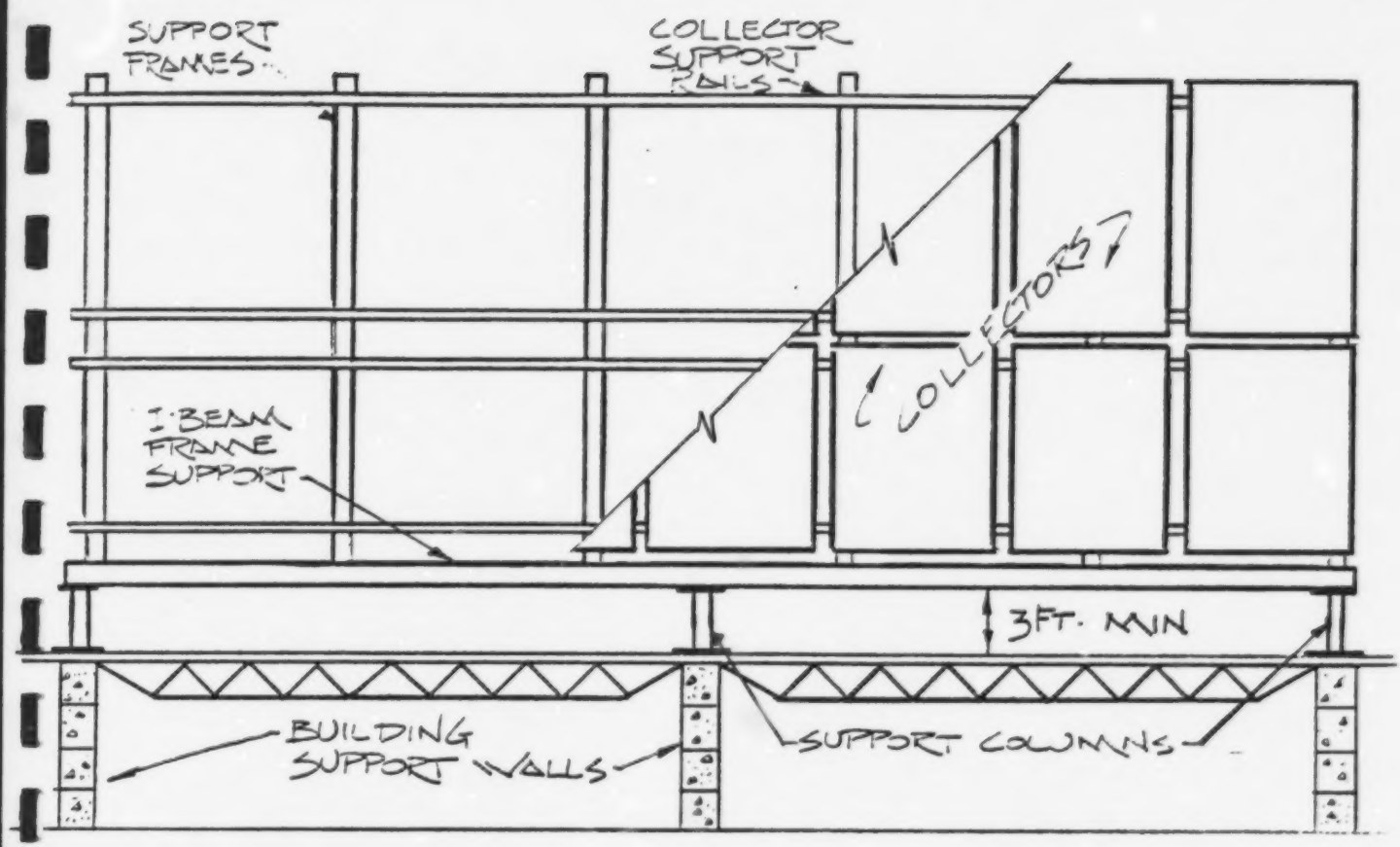


Figure 5.4). The designer must choose between many supports and light rails or few supports and heavy rails. The optimum design will depend on the type of roof. If the roof is a concrete slab or is supported by many interior walls, designers will opt for light rails and many supports. Often the support frame will be combined with the support columns, thereby eliminating the need for frame support rails. Figure 5.5 shows a wood support rack that has been used successfully in British Columbia on several buildings where the required span is short. The wood trusses are used every four feet and anchored to wooden sleepers. The sides and back are enclosed with plywood to avoid snow build-up under the collectors. This design would have to be altered in high snow load regions. Although wood racks are cheap, they have a very limited span between support columns (maximum 3 metres) and some building owners may object to the use of wood.

If the required span is large, metal racks can span distances of up to 9 metres. In these situations frame support rails made of I beams are used. The frames can then be bolted to the I beam at closer spacings, typically three metres. When metal racks are used, support frames are generally designed to hold a double bank of collectors. This reduces the total racking cost by approximately 25% and reduces the number of roof penetrations. Metal racks are generally made from welded angle iron or Unistrut® members. Unistrut® is usually used for the collector support rails because the collectors can be easily bolted to it.

The objective of any design is to minimize on-site labour. Experience has shown that racks are easier to assemble and will not rust as quickly if the frames are welded, drilled and galvanized at the factory. On-site work should consist only of bolting the structure together. Carbomastic® paint is good for touch-ups where the galvanizing has chipped off.

If the building has an inverted roof system, it may be possible to put concrete sleepers directly on the roof and avoid any roof penetrations (see Figure 5.6). The concrete sleepers are placed above the building support walls and made long and heavy enough so that the wind cannot tip the collectors over. This system has been used successfully at Downsview Postal Station B in Toronto.



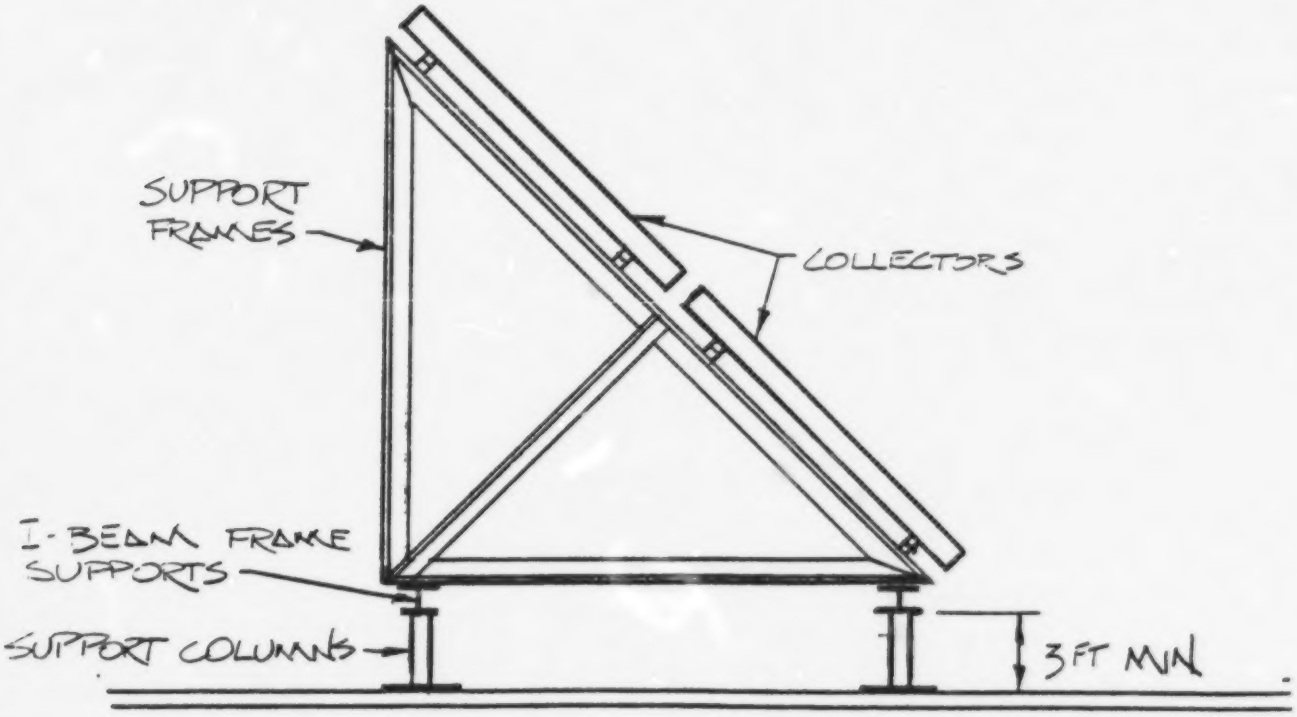


Figure 5.4 Typical Metal Collector Support Rack

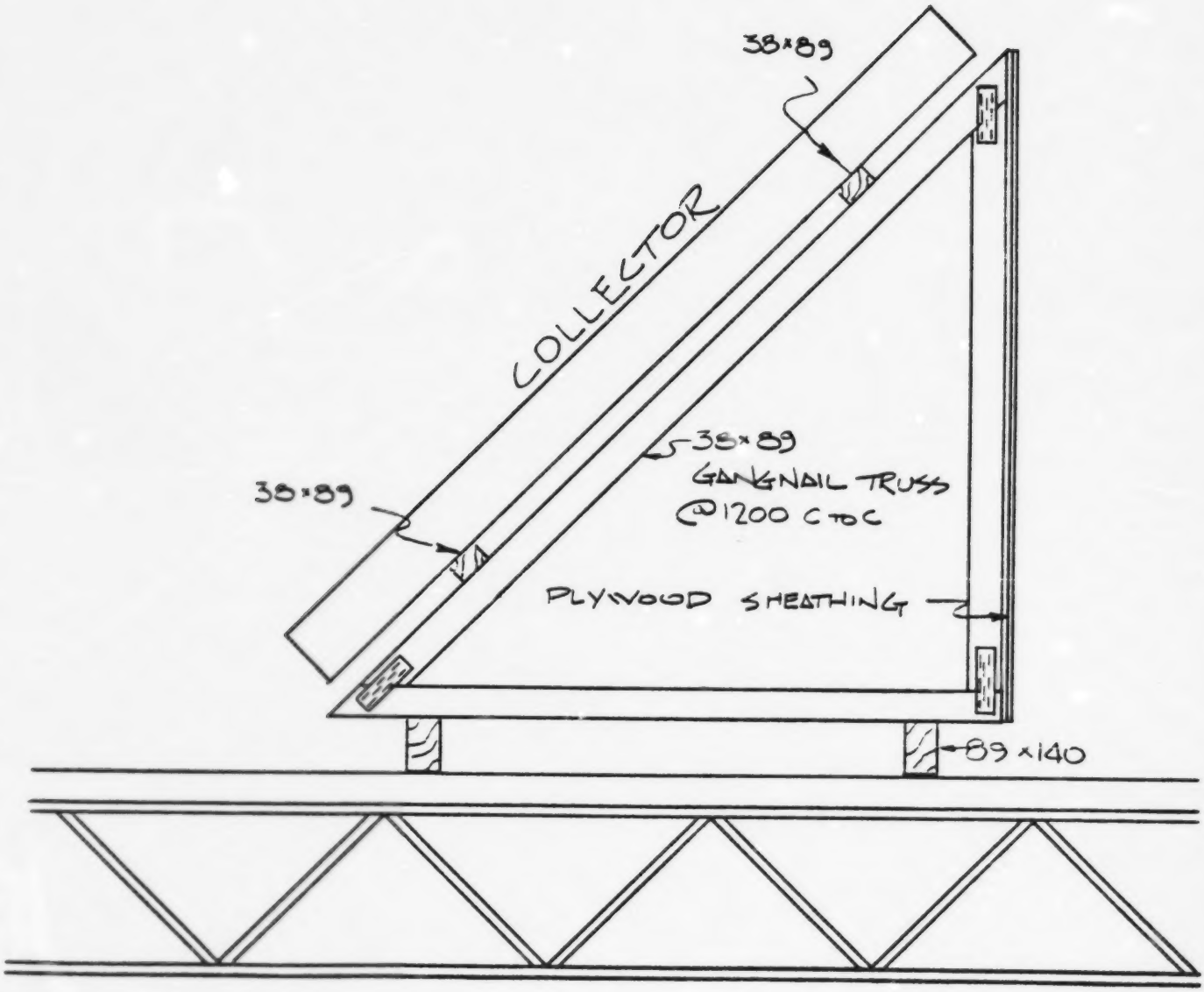


Figure 5.5 Wood Frame Collector Support Rack for Roof Mountings

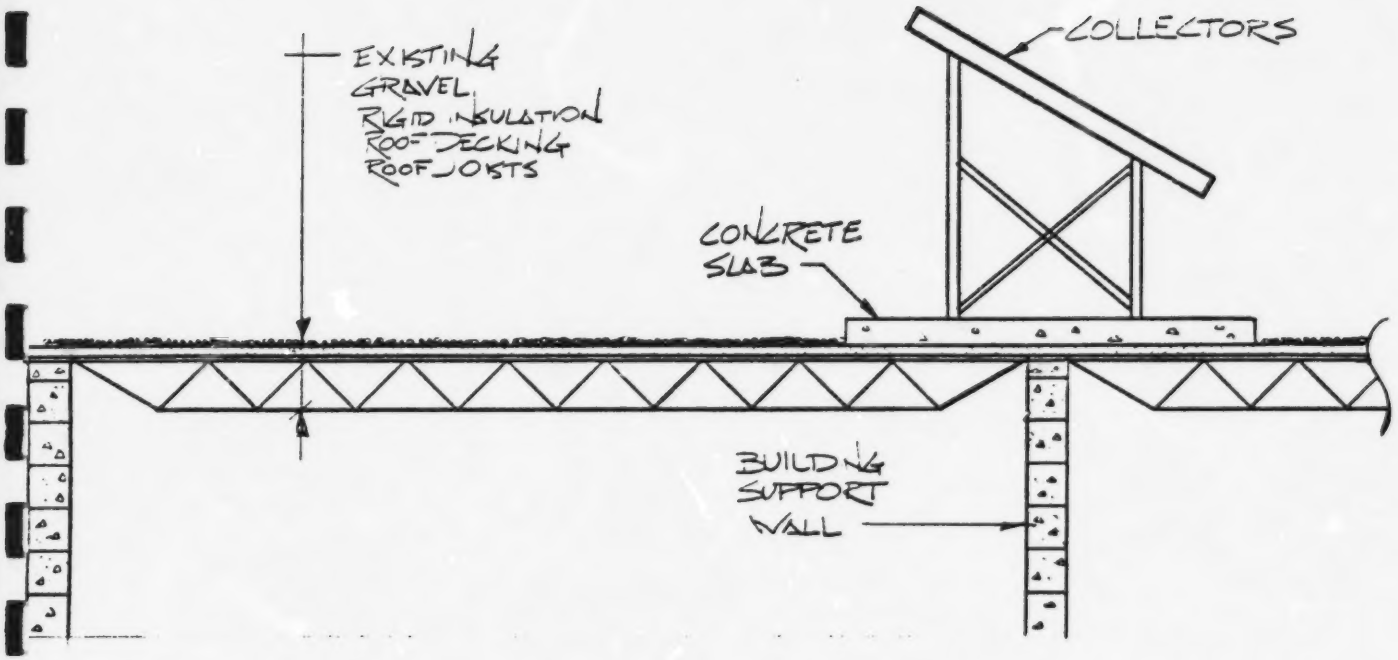


Figure 5.6 Possible Collector Support Rack for Inverted Roof Systems

6. STORAGE TANKS

The discussion of the workshop participants focussed on methods to reduce the cost of thermal storage. Participants noted three areas where system cost effectiveness could be improved: amount of storage, new tank materials and improved tank thermal stratification.

6.1 Storage System Size

The amount of storage required for a solar system is generally a function of how well the availability of solar radiation matches the water heating load; the better the match, the less storage required. The amount of storage required is a function of the percentage of the load supplied by the solar system. Five years ago, when solar systems were frequently designed to supply over 50% of the load, 50 litres per square metre was a common rule of thumb for tank size. Now systems usually are designed to supply a smaller solar fraction and use a little as 20 l/m^2. If the load is constant and continuous, storage tanks can be eliminated. For most applications, however, (e.g. nursing homes, apartments) the water heating load fluctuates enough that a storage tank is warranted. Once-through, no storage, solar systems are often only practical for large industrial applications designed to supply less than 10% of the load. During the detailed design phase designers will often use a detailed computer program like WATSUN to optimize storage size.

6.2 Storage System Selection

Large conventional metal storage tanks are generally expensive items. To reduce costs, designers have been going to multiple small tanks or plastic tanks. Tanks made from polyethylene or EPDM can be as low as one third the cost of metal tanks. The use, however, of non-pressurized or plastic storage tanks has an effect on the system design. Non-pressurized storage tanks will often require the use of a load-side heat exchanger. This may be detrimental to the system's performance if the load is intermittent or the heat exchanger is undersized. High pressure EPDM tanks, that were developed for the U.S. military, would overcome this problem. There are two potential problems with the use of plastic

(polyethylene) storage tanks. First, thermal expansion and vibration stresses can cause the plastic tank to crack at the fittings if it is fastened to rigid pipes. Second, aging of the plastic may cause weakening and splitting of the tank if the tank is unreinforced. Both of these problems can be overcome by proper design.

Because tanks 100 Imperial gallons (454 l) and under do not have to meet the Boiler and Pressure Vessel Code, it may be cheaper to use several 100 Imp. Gallon tanks rather than a single large tank. Installation may also be easier if door access is limited. Plumbing costs, however, for a multiple tank configuration would be higher. If the storage tanks are to be installed in a hot boiler room, it may be more cost effective to leave some or all of the tanks uninsulated. The cost of insulation is eliminated and the system may actually deliver more heat to the load by picking up heat from the boiler room.

6.3 Tank Stratification

Thermal stratification can improve system performance by as much as 30% over a fully mixed tank. Thermal stratification is achieved by reducing the circulation rate to the "low-flow" range (0.2 l/min./m^2). Use of several smaller tanks connected in series can promote and maintain stratification by reducing the mixing of hot and cold water. The benefit of the low-flow technique is reduced, however, for low fraction solar applications.

The use of a new technique "once-through variable volume storage" can also enhance performance. In this technique water is circulated from the city mains through the collectors to a tank at atmospheric pressure. The circulation rate is controlled such that the water is raised to the desired hot water temperature in a single pass through the collector. The volume of the storage tank varies with hot water addition and removal to the load. The major drawback to this configuration is the need to repressurize the heated water. Repressurizing hot water can present some difficult pressure-balancing problems between hot and cold water supplies.

7. HEAT EXCHANGERS

The participants of the workshop had a wide range of experience with heat exchangers. Most utilized heat exchangers manufactured by other companies to specified design requirements (typically 0.7 effectiveness). From the workshop discussion it appeared that, other than proper heat exchanger selection, there is little opportunity to reduce heat exchanger cost.

7.1 Heat Exchanger Selection

Most large commercial and industrial solar systems use plate-type heat exchangers. These units combine compactness with ease of service and high thermal effectiveness. Their cost is quite competitive with other types of heat exchangers. Other heat exchanger types include, tube-in-tube, tube-in-shell, immersed coil and thermosyphoning. In general, the solar heating system will perform better if the heat exchanger is placed on the collector side of the storage tank. (This requires that the storage tank(s) be at the same pressure as the water in the auxiliary heater.) Recent work has shown that thermosyphon (sometimes called gravity convection or side-arm heat exchangers) can be quite effective for applications where there is a large temperature difference (e.g. low flow systems).

The performance of heat exchangers is reduced by fouling. Because of its small passages, plate-type heat exchanger performance is particularly susceptible to any dirt in the system. Provision should be made to allow for the occasional cleaning of the heat transfer surfaces. Plate heat exchangers can be awkward to reassemble if the gaskets loosen during disassembly or cleaning. Tube in shell heat exchangers require a large amount of space to allow a tube bundle to be pulled out or the tubes to be reamed.

7.2 Single-Walled vs. Double-Walled Heat Exchanger

There is a major controversy currently underway concerning the use of single-walled heat exchangers in potable water systems. Plumbing codes require that toxic fluids must not be allowed to enter potable water systems. (Even tap water can become non-potable if allowed to stagnate for extended period of time.) Double-walled heat exchangers, which satisfy the plumbing codes, are available, but they are much more expensive, more difficult to acquire and less effective than single-walled units of the same size. Instead of using a double-walled heat exchanger, designs are being used that prevent the collector fluid from entering the potable water supply even if the heat exchanger leaks. The most common techniques are the use of low pressure relief valves and/or atmospheric tanks on the collector fluid side of the heat exchanger. This has not created a problem in most municipalities. Local plumbing inspectors, however, have the final word on approving the heat exchanger in a solar system.

8. SYSTEM CONTROL AND OPERATION

The discussion on controls highlighted the fact that there are two components to solar system controls: the equipment and its operation. It was noted that even if the equipment was sound, a poorly trained (untrained) operator could cause significant problems for the system.

8.1 Control Requirements

A solar controller is the most critical component for reliable solar system operation. The failure of a solar controller to do its job reliably and accurately can reduce or completely destroy the operating efficiency of a system. For this reason it is recommended that each control system include the following four basic control functions:

1. collector-storage temperature difference measurement (using matched sensor pairs),
2. storage tank over-temperature protection,
3. independent collector over-temperature protection,
4. independent system freeze protection (even for antifreeze filled systems).

The first two control functions are usually standard on solar controllers. The third and fourth functions have been found, by hard experience, to be necessary additions. Drainback systems must not fill the collectors if they are too hot or below freezing. High and low temperature, thermal snap-action switches will provide this protection when attached to the collectors. These simple low cost switches have protected drainback systems from steam explosions and freezing. Closed-loop antifreeze systems require different mechanisms for high and low temperature protection. During cold weather cold antifreeze in the collector return piping could freeze the heat exchanger when the system starts up in the morning. In this case the control system must cause the glycol to bypass the heat exchanger until it warms up. High temperature protection should consist of a heat shedding system or an automatic glycol refill system if glycol boils out.

The control system extends beyond the equipment which simply turns the pumps off and on. The control system should also include functional diagnostic devices such as warning alarms which indicate sensor failure, loss of fluid or fluid pressure. Temperature and pressure gauges should be positioned across the collector array and pump respectively to allow the operator to check system operation.

8.2 Controller Selection

There are two types of solar controllers being specified in systems today. The most common on small systems (under 200 m^2) are the prepackaged solar controllers such as those made by Independent Energy. For large systems the extra cost of custom made control systems fabricated from standard industry components such as those from Honeywell or Penn-Johnson may be appropriate. (In some rare cases, low-loss collector systems could simply function on a timer which is set to turn on and off according to when the sun should be there.)

Prepackaged controllers offer the advantages of relatively low cost, ease of replacement, and simplicity of installation. If the solar system is to operate completely independently of other processes in the facility where it is located, a prepackaged controller may suffice for a very large application. If the solar system is to be installed on an application which requires a large number of safeguards or other influencing control elements (e.g. interconnection with a heat pump system) a custom controller may be the only practical solution.

A major concern with prepackaged solar controllers is the supply of spare parts and the service they may require. If the solar controller manufacturer goes out of business there may be no replacement components or difficulties substituting another prepackaged controller. Custom controllers made from commercial HVAC equipment will have no shortage of equipment (as parts from one manufacturer are often interchangeable with another) and there is a well established service organization familiar with the equipment.

8.3 Operator Interface

It is imperative that the control system be designed to fail in a "fail-safe" mode and that such a failure be indicated by a light. There have been cases where a solar system has run improperly for weeks because of a faulty sensor and no one knew about it. A loss of solar fluid should also be indicated by an alarm or light. The operator should be instructed to re-fill the system with a glycol solution, not just water.

Perhaps one of the most significant design failings is the completeness of the operations manual. Designers must assume that the operator has no solar experience. When the system is first installed, the operator may understand the system. He may forget or not be responsible for the system when a problem occurs later. Very frequently manuals are incomplete in describing the equipment utilized and how it should work. Control system information is frequently not detailed enough for owners or servicemen to determine if there is a component failure in the controller, a system design error, or a mechanical failure in the plumbing. Installers should always keep a (good) copy of the operations manual in the event that the copy supplied to the owner is lost or misplaced.

9. PIPING/PIPE INSULATION

Piping and pipe insulation was identified by the workshop participants as an area that is often overlooked during design and installation. The participants discussed efficient piping layout, pipe and pipe insulation selection and collector interconnection techniques.

9.1 Piping Layout

The basic concept in piping design is to "keep it simple". Several years ago commercial/industrial systems were made up of many arrays of five to six collectors all connected in a reverse-return manner. The trend today is to minimize piping, especially exterior piping, by simplifying piping layout even if it results in a slight performance penalty. By using collectors with large header pipes, thirty to forty collectors can be plumbed as a single array. If a double rack of collectors is used, the collector fluid can be supplied in the bottom row and returned in the top row. The only piping required is a "U" bend at the end of the array. A third technique is to run as much of the required piping as possible inside the building and have separate roof penetrations to supply each array. Interior piping in some cases need not be insulated and is not as prone to weathering and potential damage as exterior piping. Exterior piping should not be put at a height that makes it convenient to be stood or sat upon. In other cases access to the collectors or other roof-top equipment is made difficult by the location of the piping. Figure 9.1 shows how a 160 collector system can be plumbed with almost no exterior piping using the three techniques described above. The system, of course, would have to be balanced properly (see Section 10.2).

9.2 Pipe and Pipe Insulation Selection

In most applications copper is the best choice for piping material. It can withstand high pressures and temperatures and is durable. Copper's main drawbacks are its high cost and need for soldered joints. In solar applications steel pipes can scale badly and should not be used. For systems where the designer is convinced that the piping will not experience elevated temperatures or high pressures under any circumstance,

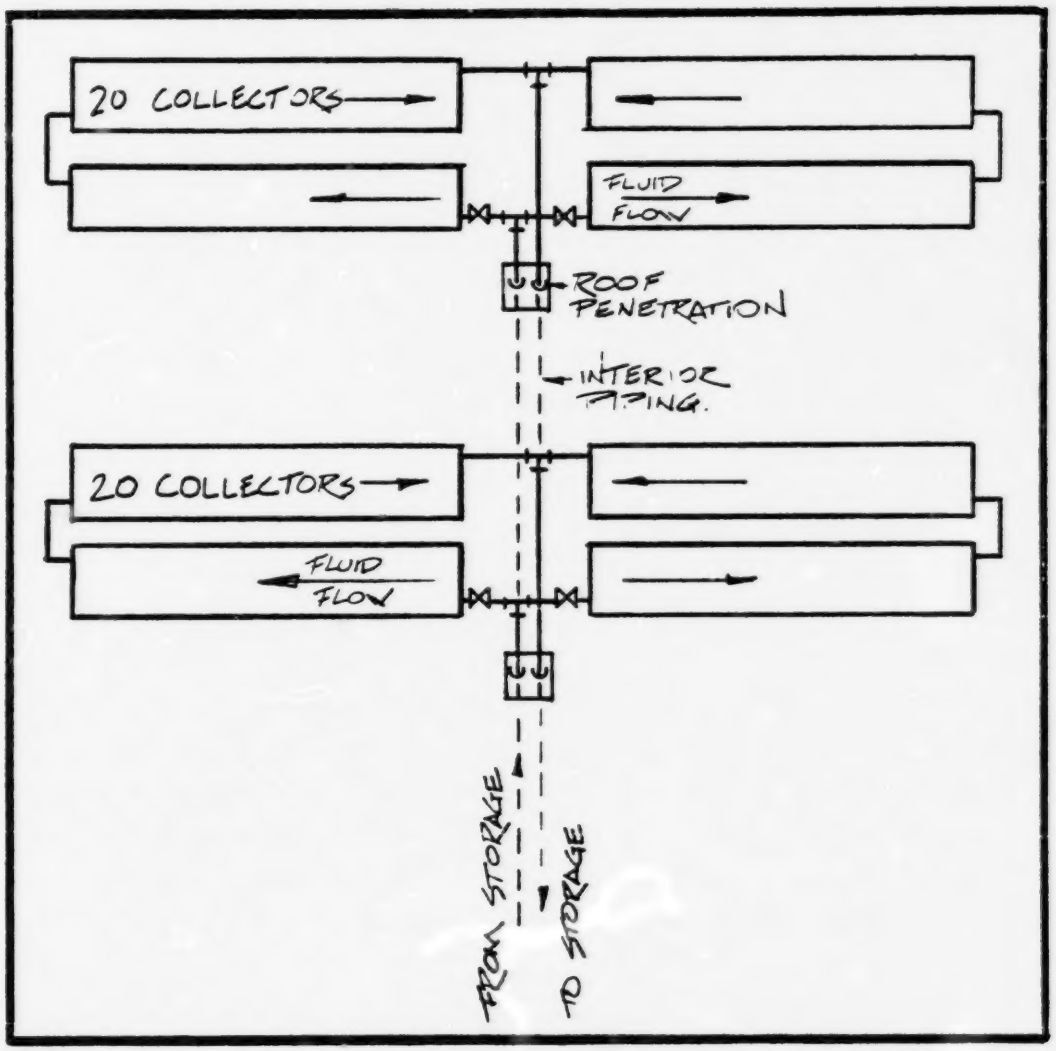


Figure 9.1 Possible Piping Arrangement for Large Roof-Mounted Solar Heating Systems

plastic piping can be used. Closed-loop systems should not use plastic piping. PVC can be used, although the higher temperature CPVC would be a more reliable product. Because it will sag when it becomes hot, plastic piping should be sloped and supported at least twice as much as copper piping. Many designers avoid using plastic piping outside because of the danger of pipe sagging causing water to freeze in the pipe.

There are many materials that can be used to insulate piping. For exterior piping the prime concern is that the insulation remain effective even if it gets wet. Experience has shown that rain, snow or condensation may eventually get inside any insulation jacket. Because of this, fiberglass is not recommended for exterior insulation. Isocyanurate or urethane covered with a vinyl jacket has proven to be effective outdoor insulation. High temperature polyethylene insulation (Senflex®) appears to also work well on exterior piping. Insulation jacketing tape should not be put on cold because it will not seal well. Armaflex® insulation rots away over several years when exposed to ultraviolet radiation. Although there is a U-V paint available for this product, it must be re-applied every few years.

For interior piping fiber glass or Armaflex are probably the best choices. Armaflex, however, can melt off hot piping. Most of the other insulations are not fire-retardent. In many cases interior pipe insulation may not be necessary. If plastic piping is used or typical collector outlet temperatures are below room temperature, the cost of interior insulation may not be justified.

9.3 Collector Interconnection

The method of collector interconnection has often been a weak link in system design. Three techniques are often used: silicone hose, expansion bellows and Victaulic couplings. Victaulic couplings have been prone to leakage and, as such, are not used widely. Soldered pipe connections in combination with expansion bellows have worked reliably. The major concern is that water not get into the bellows and freeze.

Silicone hose can work. The main problem is that the hose clamps can loosen and cause collector fluid to leak. It is wise to check the collector piping and collector interconnection several weeks after the installation is completed. Hose clamps will often have to be re-tightened and insulation re-applied. Otiker® hose clamps seem to be able to maintain pressure. Most designers, however, are not using silicone hose for closedloop or pressurized systems.

10. PUMPS, VALVES AND OTHER COMPONENTS

Other components that the workshop participants discussed are covered in this section. The discussion focussed on improving system operation specifically pump selection, flow balancing in arrays, monitoring requirements and vents to allow collector drainage.

10.1 Pumps

Pumps used in solar systems are the same type as those used in most hydronic heating systems. Some solar system designers have found it advantageous to utilize several smaller "disposable" pumps in series to provide the head and flow required in medium-sized applications. Ideally a flow-switch alarm would be provided to indicate insufficient flow caused by a pump failure. In-line strainers are not usually necessary in closed-loop all-copper or all-plastic piping systems if the pipes have been well flushed.

10.2 Balancing Solar Systems

Three techniques are used to balance solar systems. Some designers find the best procedure is to design the solar plumbing in a reverse-return configuration and size the piping to maintain a constant pressure drop. This technique is probably the least accurate and may be expensive if a lot of additional piping is needed. The second technique uses multiple thermometers or digital temperature sensors to measure the temperature rise across each collector array. (Unused sensor positions on the controller could be used for this purpose.) Ball-valves are usually used to provide the necessary balancing of individual solar arrays. (Remove the handles of set balancing valves to prevent tampering.) Automatic flow control valves and flow orifice flow-measurement devices can be used but may be too expensive to justify their use.

10.3 Diagnostic/Monitoring Equipment

The value of diagnostic and/or monitoring equipment is only really appreciated when there are difficulties with the solar system. Every solar system should have sufficient equipment to allow the operation of the pump and the solar collectors to be checked. As a minimum it would consist of only pressure gauges across the pumps and two thermometers. Additional useful information could be supplied by an elapsed-time (ET) meter. Connected to the solar pump the ET meter will provide some indication of whether the system operates when you are not there. Flow totalizers (as opposed to flow meters) can also provide information as to how the system operated when you are not there. Heat integrating meters are expensive and are normally only used when the owner is paying for the energy delivered by the solar system.

10.4 Vents

Vents installed outdoors in solar systems have not operated reliably. When installed on the top of collectors for the purpose of breaking a vacuum, vents have frequently frozen closed and failed to assist in draining the collectors. The current strategy is to use a drainback tank with an oversized or open collector return line which allows air to travel from inside the building into the collectors. If the designer so desires, a vacuum breaker may be placed in a heated space as close to the collectors as possible. The vacuum breaker must be accessible for cleaning and regular inspection.

11. CONCLUSIONS

This report has described techniques used by designers to improve the effectiveness of solar heating systems. The techniques may be categorized as to purpose: to reduce costs, to improve performance and to provide long-term reliability. A short summary of the techniques follows.

Reduce Costs

- reduce design and marketing costs by focussing on one building sector
- use seasonal or water-based systems in Vancouver-Victoria region
- ground or wall mount collectors where feasible
- orient roof mounted collectors along building support walls
- support collectors against penthouse or upper roof level
- locate collector support rack perpendicular to roof joists
- use wood-frame racks whenever possible
- use metal rods instead of concrete posts to anchor collector supports to ground
- on inverted roof systems use long concrete slabs to anchor collectors
- weld, drill and galvanize support frames at the factory
- for roof-mountings use a double bank of collectors
- use small or no storage tank for continuous load low-fraction solar systems
- use multiple 100 Imperial gallon tanks instead of one large tank
- use polyethylene or EPDM storage tanks
- reduce or eliminate tank insulation for hot boiler room installations
- use single-walled heat exchangers and provide other safety features to prevent glycol from entering potable water

- reduce piping by plumbing many collectors together in an array instead of many reverse-return arrays
- reduce piping in double-banked collectors by supplying the fluid in the bottom row and returning through the top row
- use CPVC piping with no interior insulation for low temperature open-loop systems
- use multiple small pumps instead of one large pump
- balance arrays by using unused sensor positions on the system controller
- use flow control valves, outdoor air vents and strainers only when they are providing a useful function

Improve Performance

- select applications that require heating of mains water
- measure and calculate (using fuel and water bills) water heating load)
- design for low solar fraction (under 40%)
- promote tank thermal stratification by designing for low collector flow and multiple tanks connected in series

Provide Long-Term Reliability

- use spool valves in draindown systems
- provide redundant freeze protection for seasonal systems
- ensure freeze valves properly re-close
- use drainback systems where possible and consider use of antifreeze as collector fluid
- provide a heat shedding or automatic antifreeze refill system for closed-loop systems
- remove handles from balancing valves
- use Carbomastic® paint to touch-up chipped galvanizing
- provide thermal expansion and vibration isolation between metal pipes and plastic tanks
- reinforce and support plastic tanks
- clean heat exchangers as a part of the regular maintenance plan

- do not damage plate heat exchanger gaskets during disassembly
- provide independent collector over- and under- temperature protection (e.g. snap-action switches)
- provide warning lights for possible system failures
- use custom-designed controllers for large solar heating systems
- provide a complete operations manual
- minimize exterior piping
- avoid locating piping so as to provide a "convenient" step or seat
- take care when using plastic piping by providing additional support and slope
- use urethane or isocyanurate (and not fibreglass) insulation for exterior insulation
- use fibreglass insulation for interior insulation
- do not apply insulation jacketing tape during cold weather
- use soldered connections and expansion bellows for collector interconnection
- if silicone hose is used for collector interconnection use Otiker® clamps
- provide as much diagnostic equipment as possible including an elapsed time meter or a flow totalizer
- locate air vents/vacuum breakers indoors or oversize collector return piping to provide collector drainage